

Rare Kaon Decays: Progress and Prospects

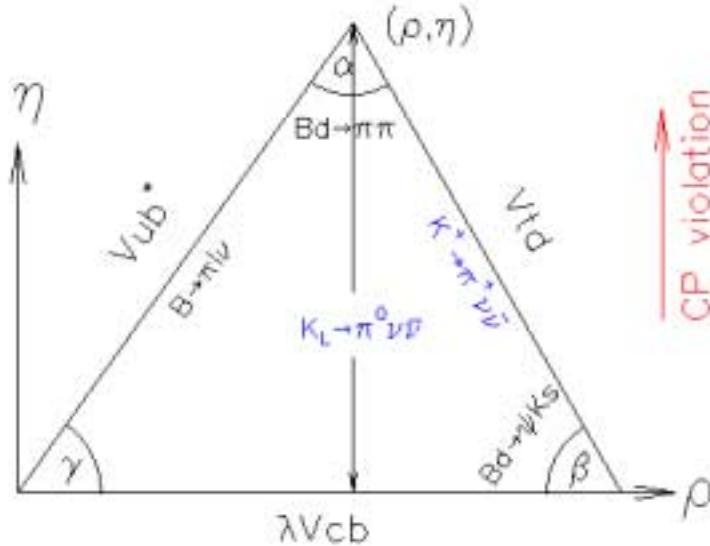
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Overview of Rare Kaon Decays

<i>Exotic Searches</i>	$K_L^0 \rightarrow \mu^- e^-$ LFV $K^+ \rightarrow \pi^+ f^-$ "Axions" $K^+ \rightarrow \pi^+ \gamma$ Ang. Mom.
<i>SM Parameters and BSM Physics</i>	$K_L^0 \rightarrow \mu^+ \mu^-$ $ V_{td} $ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ $ V_{td} $ $K_L^0 \rightarrow \pi^0 e^+ e^-$ CP violation $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ CP violation
<i>Low Energy QCD Chiral Perturbation Theory</i>	$K_L^0 \rightarrow \gamma l^+ l^-$ $l = e, \mu$ $K^+ \rightarrow \pi^+ l^+ l^-$...Radiative decays

Standard Model CP Violation



$$\left\{ \begin{array}{l} \text{"Jarlskog invariant" } |J_{CP}| \\ 2A_\Delta = \left| \text{Im} V_{ts}^* V_{td} \right| \lambda \left(1 - \frac{\lambda^2}{2} \right) \end{array} \right\}$$

Four Super-clean Processes will challenge the SM Picture

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

$$|V_{ts}^* V_{td}|$$

E 949 , CKM

$$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$$

$$\text{Im}(V_{ts}^* V_{td})$$

KOPIO

$$B_d \rightarrow \psi K_S$$

$$\sin(2\beta)$$

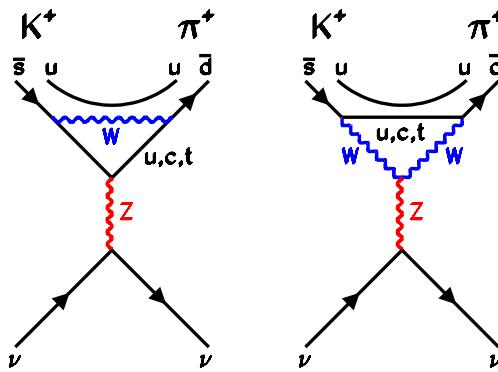
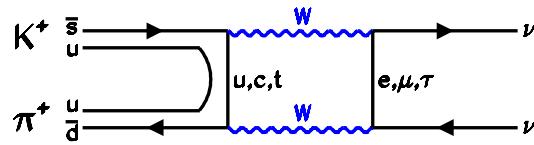
CDF, BABAR, BELLE

$$\frac{x_s}{x_d}$$

$$\left| \frac{V_{ts}}{V_{td}} \right|$$

CDF, D0, LHCb, BTeV

$K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model



	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$
Top Quark Dependence	$ \lambda_t = V_{ts}^* V_{td} $	$\text{Im}(\lambda_t) = \text{Im}(V_{ts}^* V_{td})$
SM BR (10^{-11})	7.2 ± 2.1	2.6 ± 1.2
Est. Theory Uncertainty	7% (charm)	2%

- Negligible long distance effects (10^{-13}).
- Hadronic matrix elements from isospin analog $K^+ \rightarrow \pi^0 e^+ \nu_e$.

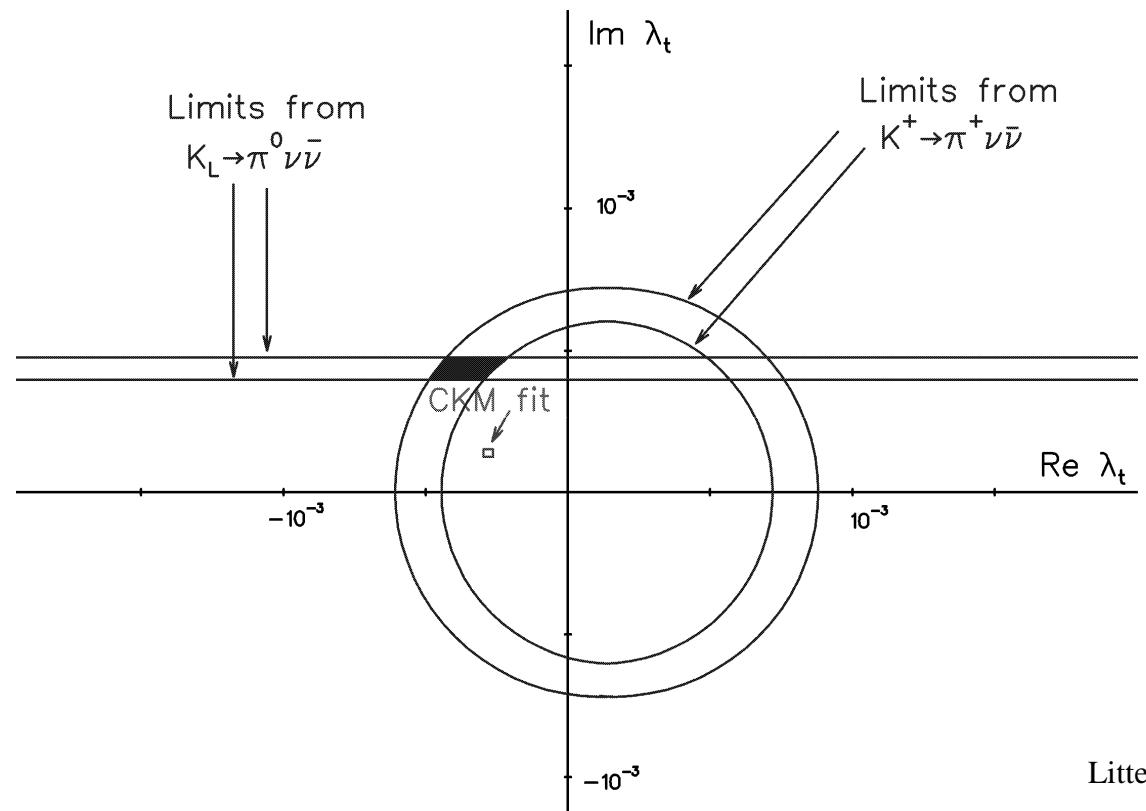
Standard Model (*Buras*):

$$\text{Im } \lambda_t = \text{Im} V_{ts}^* V_{td} = \eta A^2 \lambda^5$$

$$R(K_L^0 \rightarrow \pi^0 \bar{\nu}\bar{\nu}) = 1.8 \times 10^{-10} \left(\frac{\text{Im } \lambda_t}{\lambda^5} X(x_t) \right)^2$$

$$\sim 4.1 \times 10^{-10} A^4 \eta^2 = 2.6 \pm 1.2 \times 10^{-11}$$

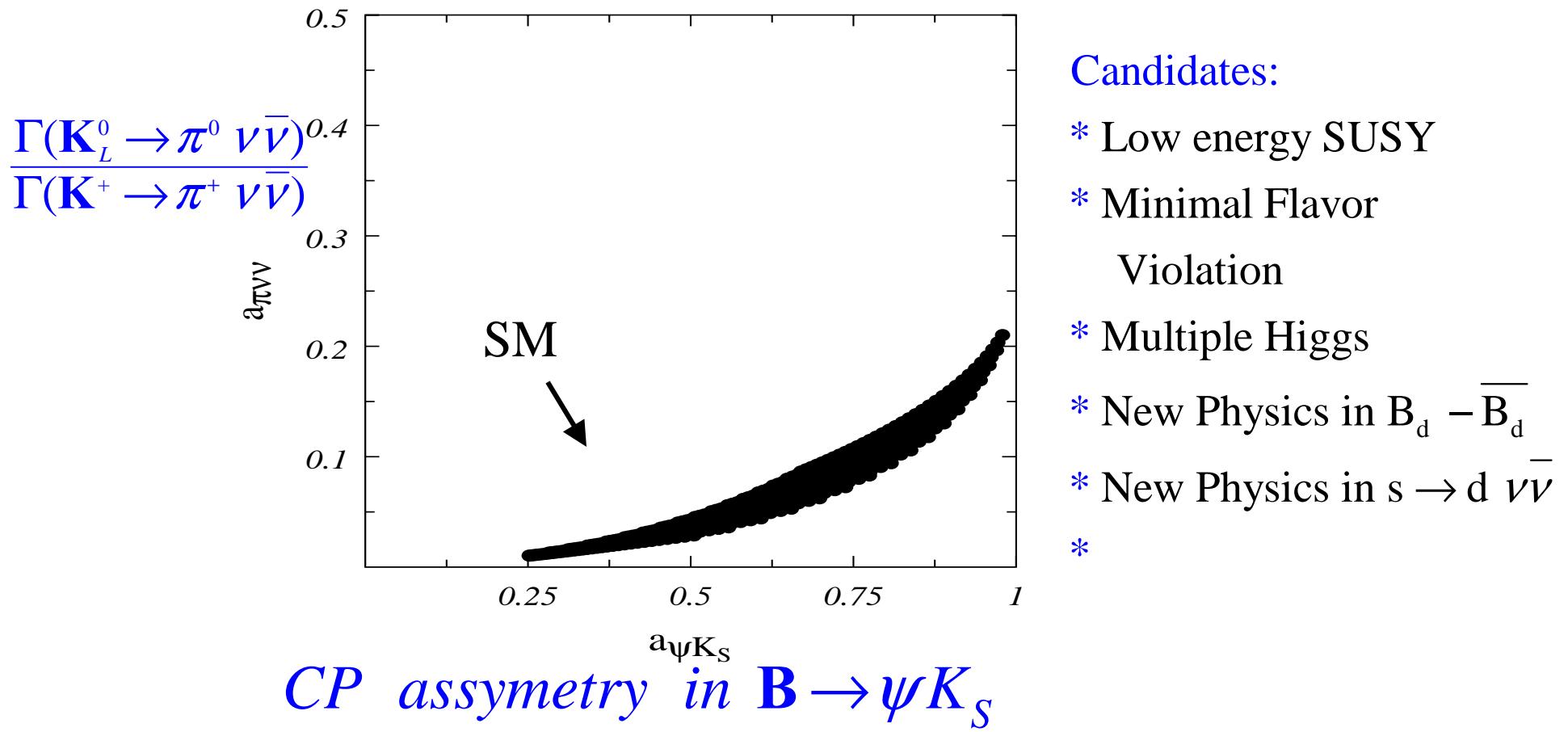
$$R(K^+ \rightarrow \pi^+ \bar{\nu}\bar{\nu}) \sim 1.0 \times 10^{-10} A^4 \left[\eta^2 + (\rho_0 - \rho)^2 \right] = 7.2 \pm 2.1 \times 10^{-11}$$



Littenberg

$\mathbf{B} \rightarrow \psi K_S$ and $\mathbf{K} \rightarrow \pi \nu \bar{\nu}$

Differences sensitive to new physics – virtually free of uncertainties.



(Nir and Worrah, Phys. Lett. **B319** 1998)

(Buras,1999)

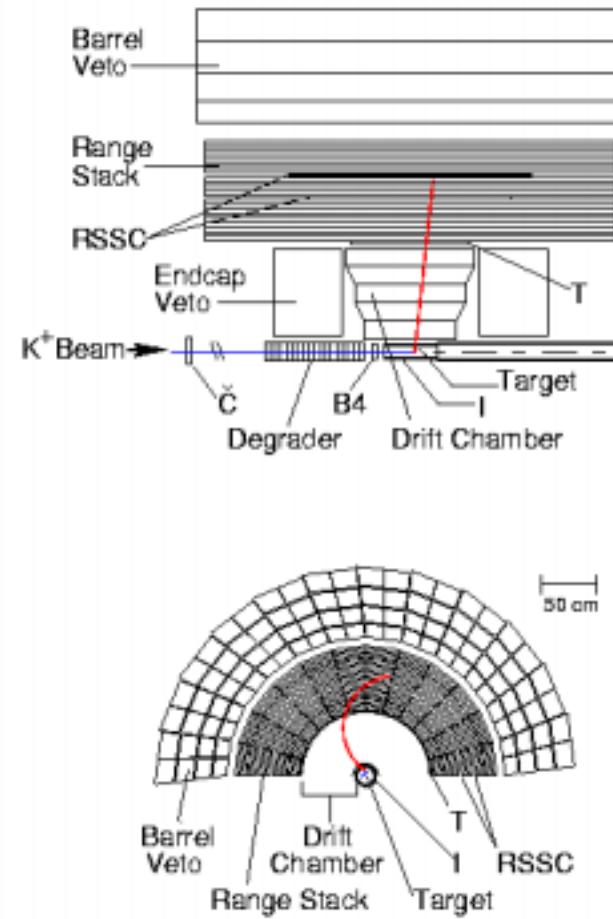
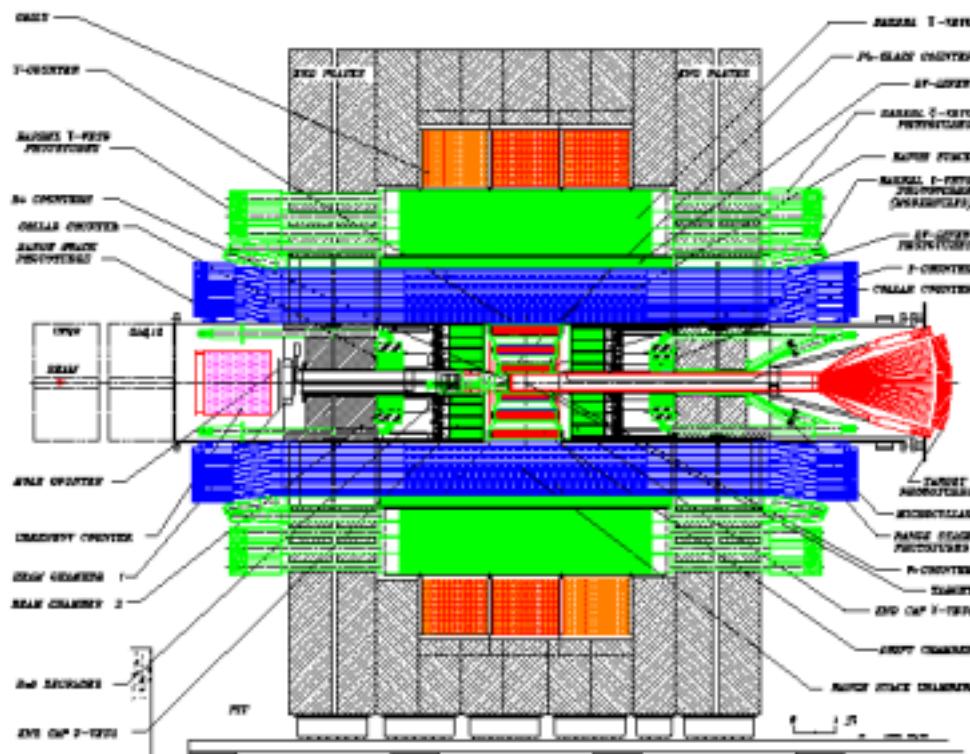
Comparison of Precision from Proposed K and B Measurements

$$\sigma(|V_{cb}|) = \pm 0.002(0.001)$$

	$K \rightarrow \pi \bar{\nu} \bar{\nu}$	B-Factory Era	LHCb/BTeV
$\sigma(V_{td})$	$\pm 10\%(9\%)$	$\pm 5.5\%(3.5\%)$	$\pm 5\%(2.5\%)$
$\sigma(\bar{\rho})$	$\pm 0.16(0.12)$	± 0.03	± 0.01
$\sigma(\bar{\eta})$	$\pm 0.04(0.03)$	± 0.04	± 0.01
$\sigma(\sin 2\beta)$	± 0.05	± 0.06	± 0.02
$\sigma(\text{Im } \lambda_t)$	$\pm 5\%$	$\pm 14\%(11\%)$	$\pm 10\%(6\%)$

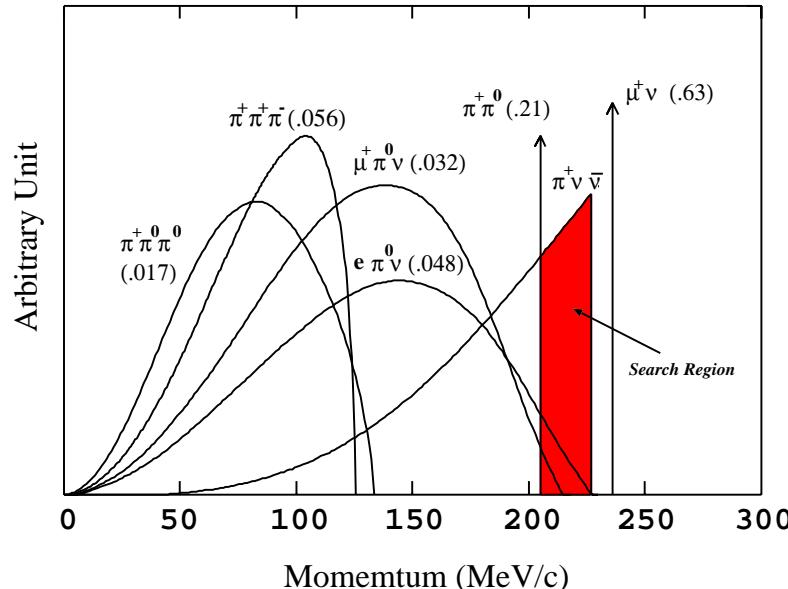
BNL E787(E949)

Measurement of $K^+ \rightarrow \pi^+ \bar{v}\bar{\nu}$



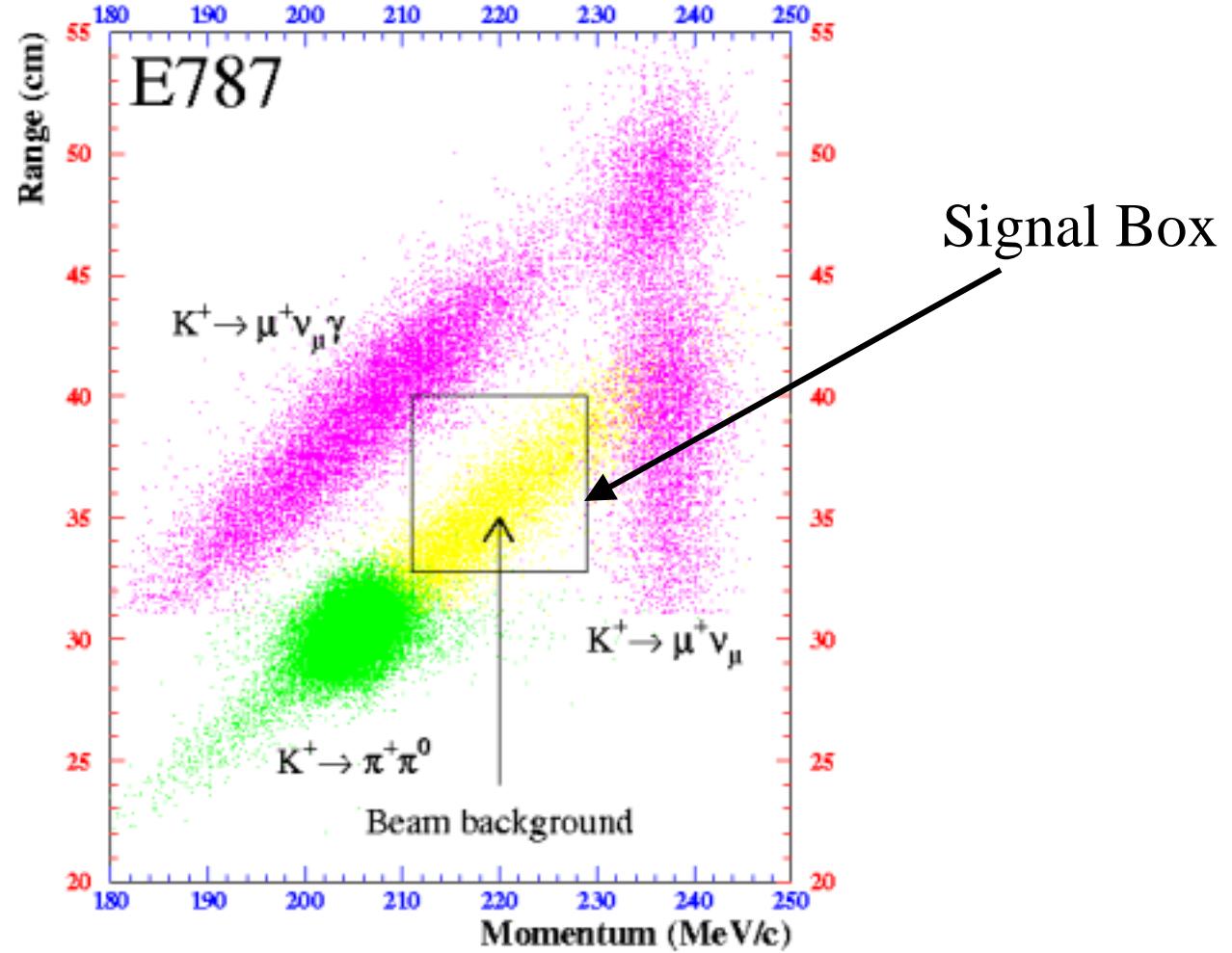
Special Features of Measuring $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Background processes may exceed signal by $>10^{10}$



- Determine everything possible about the K^+ and π^+
 - * π^+/μ^+ particle ID better than 10^6 ($\pi^+ - \mu^+ - e^+$)
- Eliminate events with extra charged particles or **photons**
 - * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~10)
 - * Predict backgrounds *from data*: dual independent cuts
 - * Use “Blind analysis” techniques
 - * Test predictions with “outside-the-box” measurements
- Evaluate candidate events with S/N function

Background Processes: Range vs. Momentum

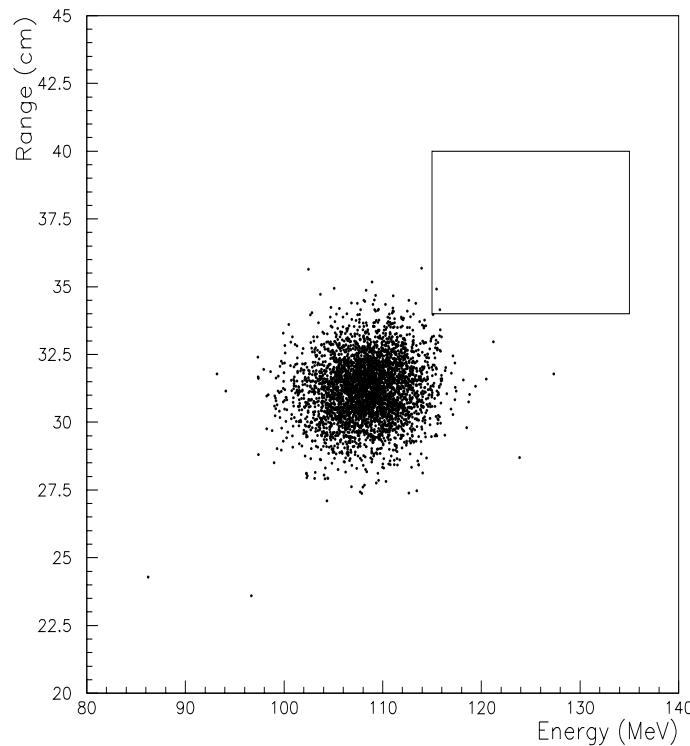


$K^+ \rightarrow \pi^+ \pi^0$ Background Suppression

Dual cuts: γ Veto and Kinematics (P,R,E...)

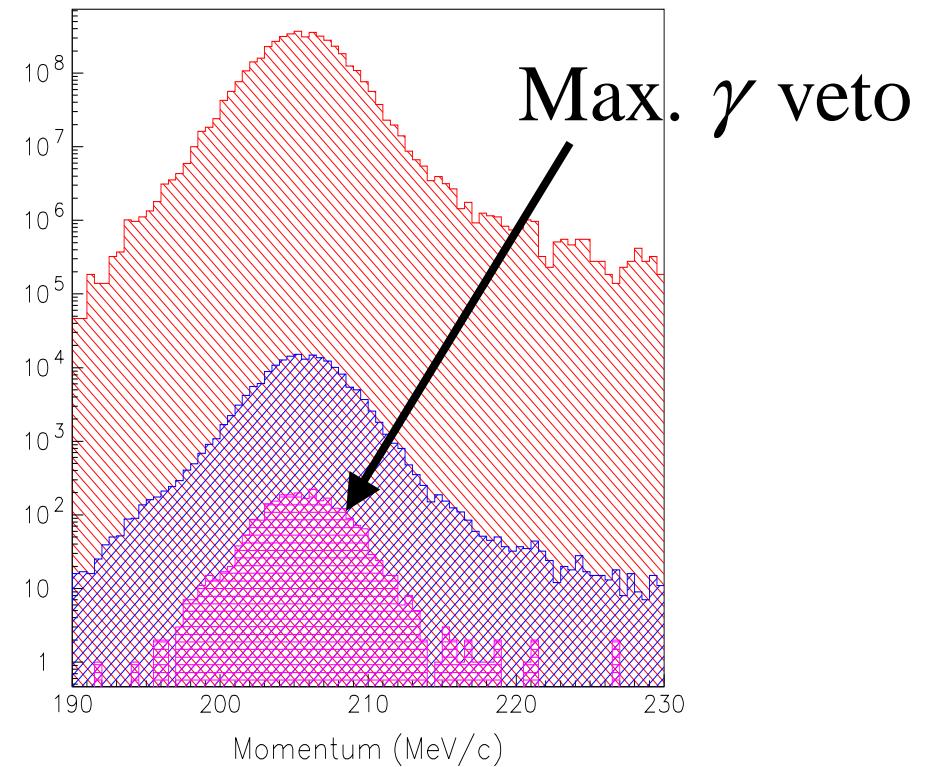
γ Veto Reversed

Range vs. Energy



γ Veto Applied

Momentum



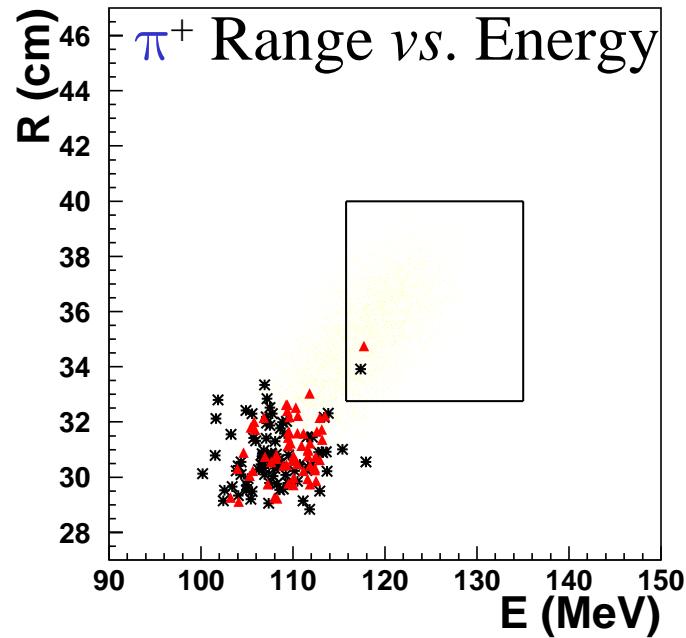
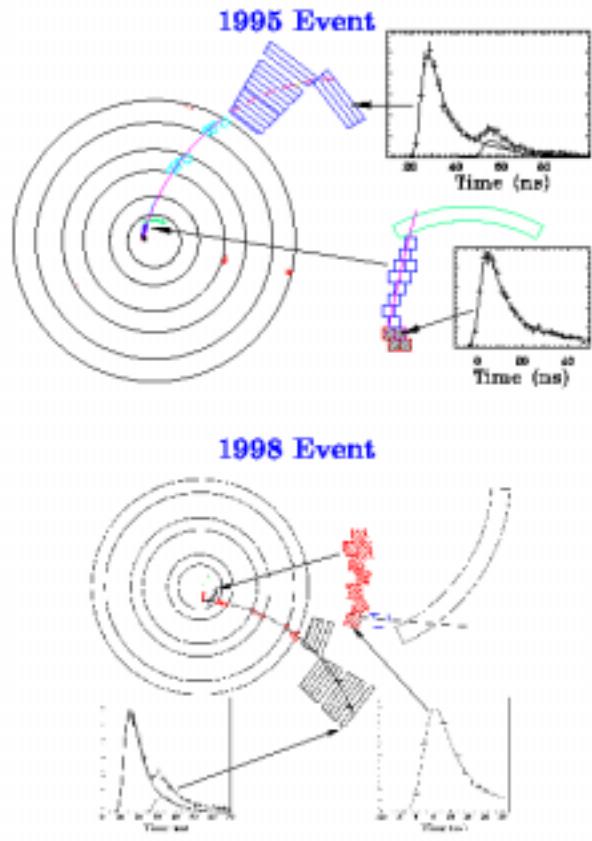
Check for correlations

E787 Background Estimates

Source	Events
<hr/>	
$K^+ \rightarrow \mu^+ \nu$	0.04 ± 0.01
$K^+ \rightarrow \pi^+ \pi^0$	$0.05 \pm^{0.04}_{0.03}$
Beam π	0.02 ± 0.02
Charge exch.	0.03 ± 0.01
<hr/>	
Total	$0.15 \pm^{0.05}_{0.04}$

$$N_{K^+} = 5.9 \times 10^{12} \quad \text{Efficiency } \epsilon = 2 \times 10^{-3}$$

E787 2002: Two $K^+ \rightarrow \pi^+ \bar{v} v$ Candidates



Event	P (MeV/c)	R (cm)	E (MeV)	S/N
1995	218.2	34.8	117.8	35
1998	213.8	33.9	117.1	3.6

$$N_{K^+} = 5.9 \times 10^{12} \quad \text{Efficiency } \epsilon = 2 \times 10^{-3}$$

Estimated Background: 0.15 ± 0.05 events

Branching Ratio

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.57 \pm^{1.75}_{0.82} \times 10^{-10}$$

Consistent with SM: $(0.72 \pm 0.21) \times 10^{-10}$

Estimated probability of being due to background only : 0.02%

Limits on $\lambda_t \equiv V_{ts}^* V_{td}$ (Independent of B system, $\varepsilon_K, \varepsilon'$)

$$2.9 \times 10^{-4} < |\lambda_t| < 1.2 \times 10^{-4} \text{ (68% C.L.)}$$

$$-0.88 \times 10^{-3} < \text{Re}(\lambda_t) < 1.2 \times 10^{-3} \text{ (68% C.L.)}$$

$$\text{Im}(\lambda_t) < 1.1 \times 10^{-3} \text{ (90% C.L.)}$$

Impact of E787 and E949 on Flavor Physics

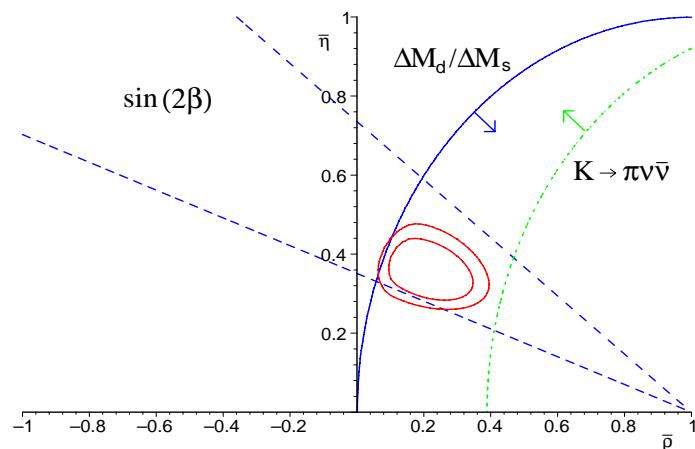


Figure 2: Allowed region in the $\bar{\rho} - \bar{\eta}$ plane using only theoretically *clean* observables: 90% C.L. interval imposed by $\sin(2\beta)$ (dashed); 90% C.L. limit from the upper bound on $\Delta M_{B_d}/\Delta M_{B_s}$ (full); 90% C.L. limit from the lower bound on $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ (dotted). For comparison the 68% and 90% C.L. ellipses from the global fit in Fig. 1 are also shown.

E787 and other clean
observables (90% CL)

E949 at the
E787 BR

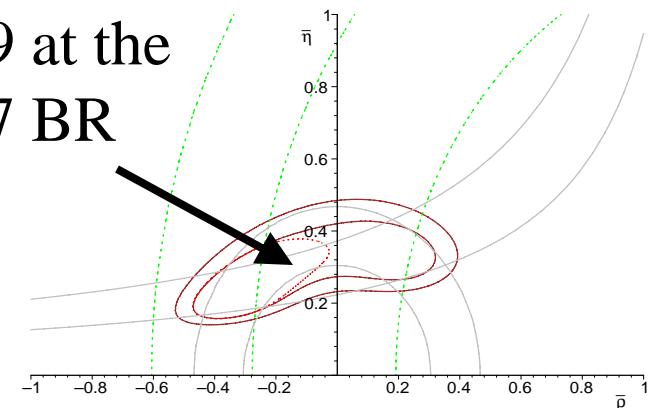


Figure 3: Allowed region in the $\bar{\rho} - \bar{\eta}$ plane with the inclusion of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and without $B_d - \bar{B}_d$ data. The two external contours denote 68% and 90% confidence intervals; the inner (dotted) one is the 68% confidence interval under the assumption that experimental error in (1) is reduced by a factor two.

*Possible E949 result
favoring Non-SM*

$$K^+ \rightarrow \pi^+ \bar{\nu} \nu$$

Future Prospects

BNL *E949 (2002-)*

Upgrade of E787 detector

Improved photon vetos – truly hermetic coverage

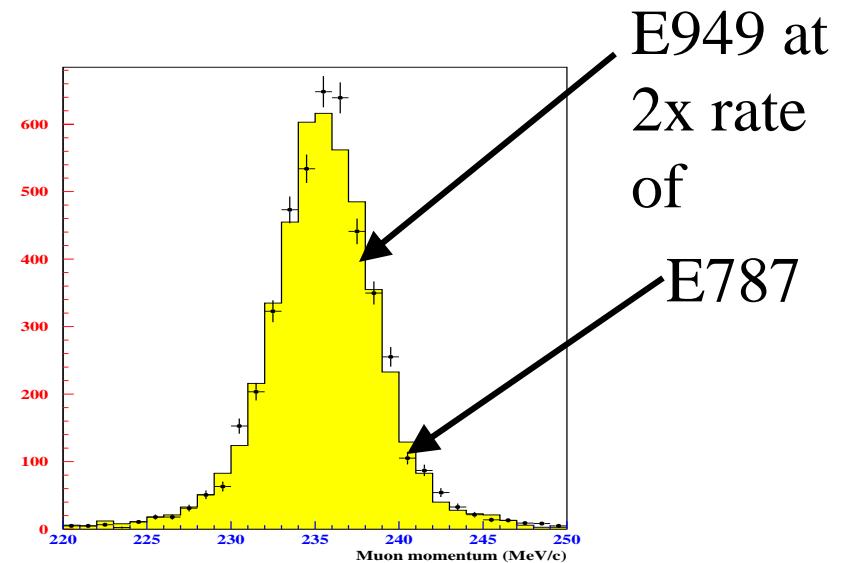
Access to the low momentum region

Sensitivity goal: $<10^{-11}$

Order of magnitude improvement beyond E787

Factor 5-10 below the SM prediction

μ^+ Momentum from $K^+ \rightarrow \mu^+ \nu$



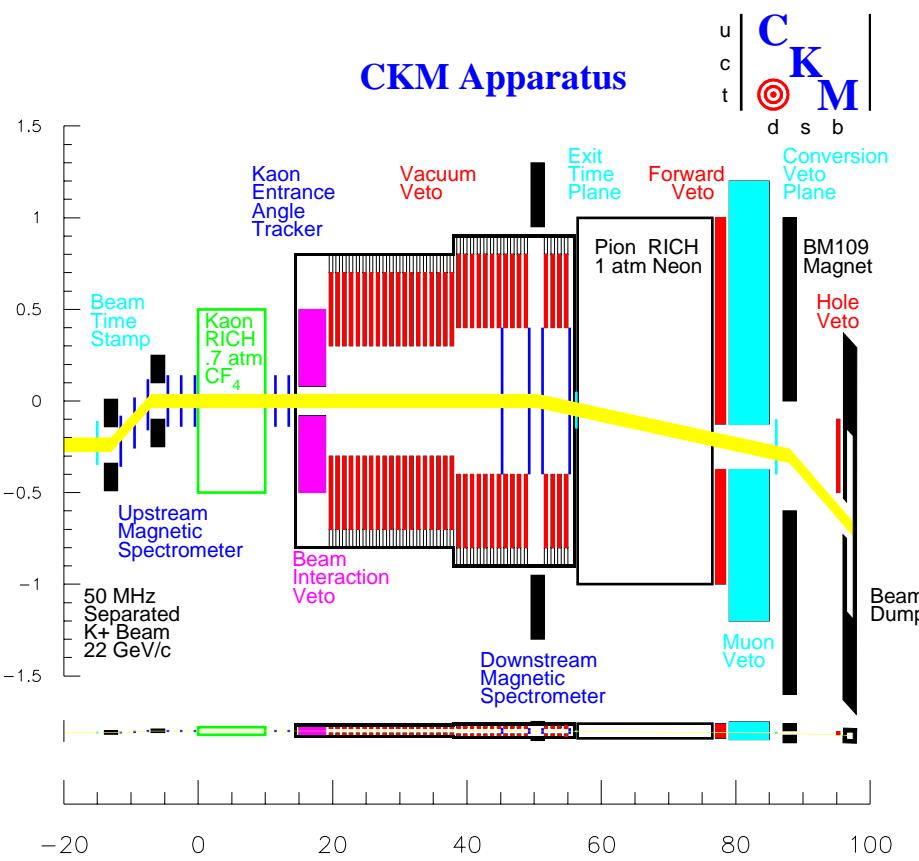
$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

FNAL CKM (~2007-)

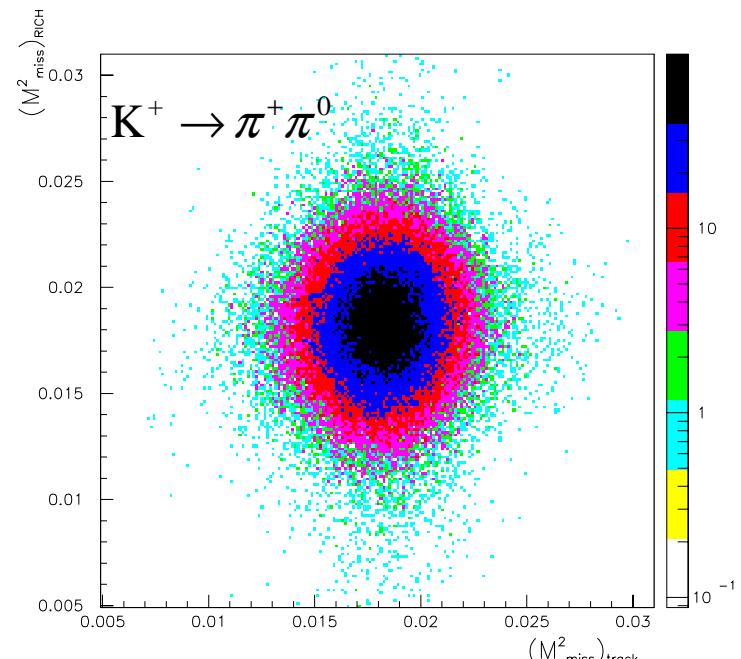
New *in-flight* technique - RF-separated K beam

Particle ID : RICH

Sensitivity goal: $<10^{-12}$

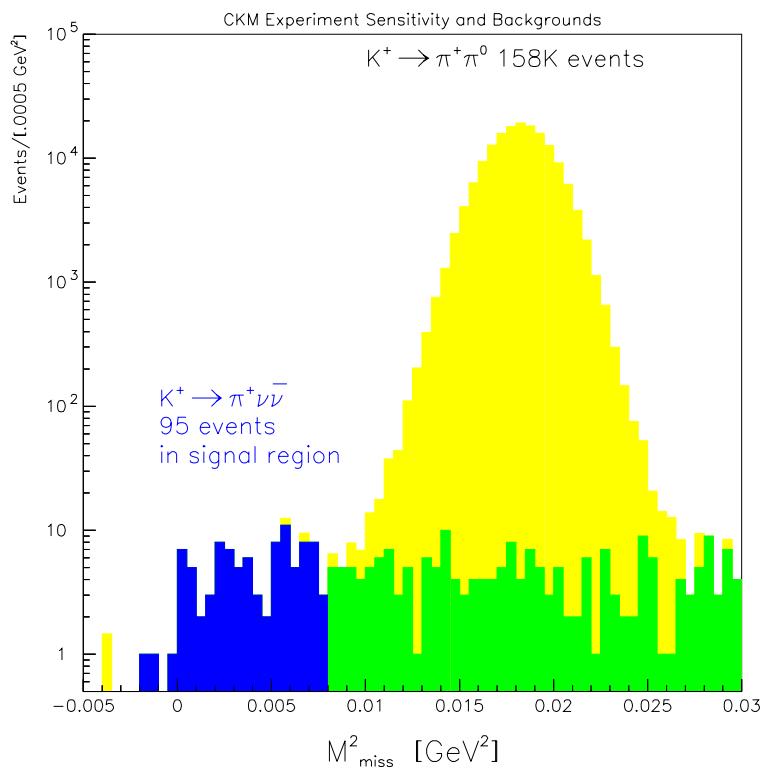


Momentum simulation:
RICH vs Tracking



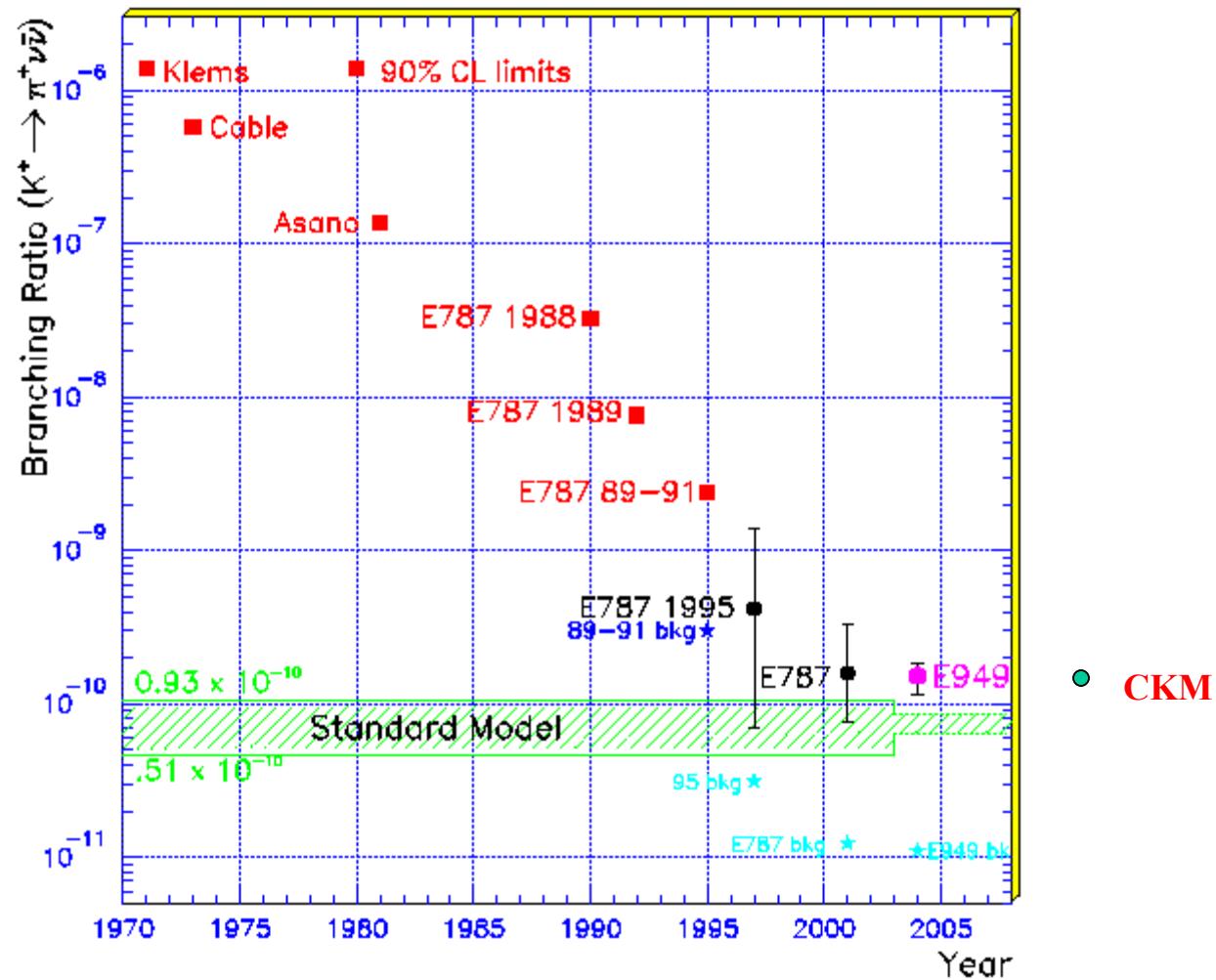
$M^2_{missing}$

CKM Goal: 100 events with S/N>7



Background source	Effective BR ($\times 10^{-12}$)
$K^+ \rightarrow \mu^+ \nu_\mu$	< 0.04
$K^+ \rightarrow \pi^+ \pi^0$	3.7
$K^+ \rightarrow \mu^+ \nu_m u \gamma$	< 0.09
$K^+ A \rightarrow K_L X, K_L \rightarrow \pi^+ e^- \bar{\nu}_e$	< 0.14
$K^+ A \rightarrow \pi^+ X$ in trackers	< 4.0
$K^+ A \rightarrow \pi^+ X$ in residual gas	< 2.1
Accidentals (2 K^+ decays)	0.51
Total	< 10.6

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Measurements vs. Year



$K^+ \rightarrow \pi^+ x$ and Global Family Symmetry

[Wilczek (1982), Gelmini et al. (1983), Feng et al. (1998)]

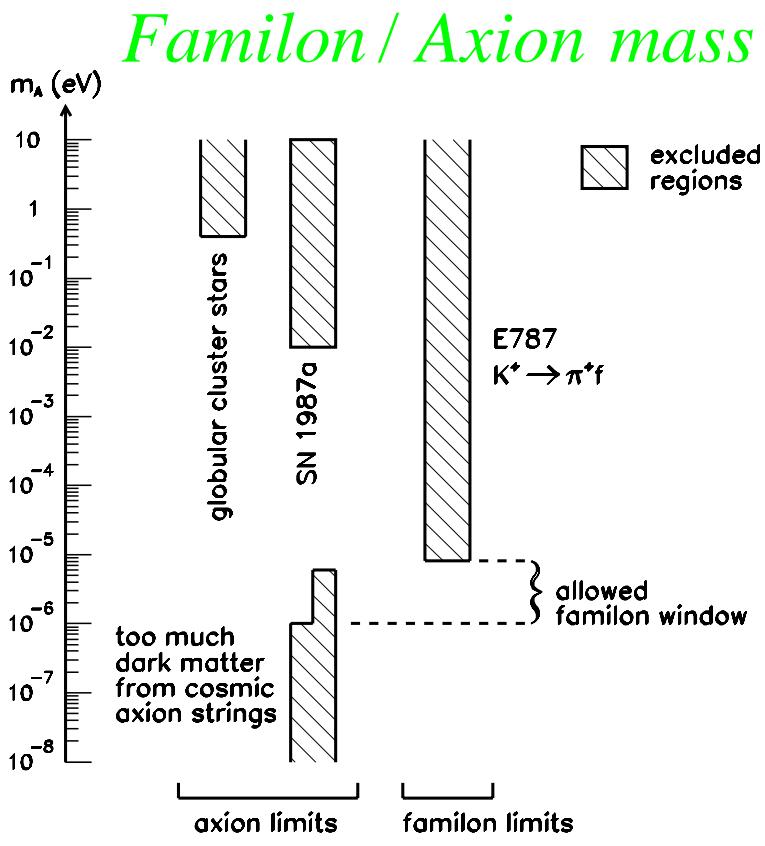
Motivation: Explain the replication of families

Postulate: Global Family Symmetry spontaneously broken at large mass scale $\{F\} \rightarrow$ Goldstone Boson "FAMILON $\{f\}$ ".

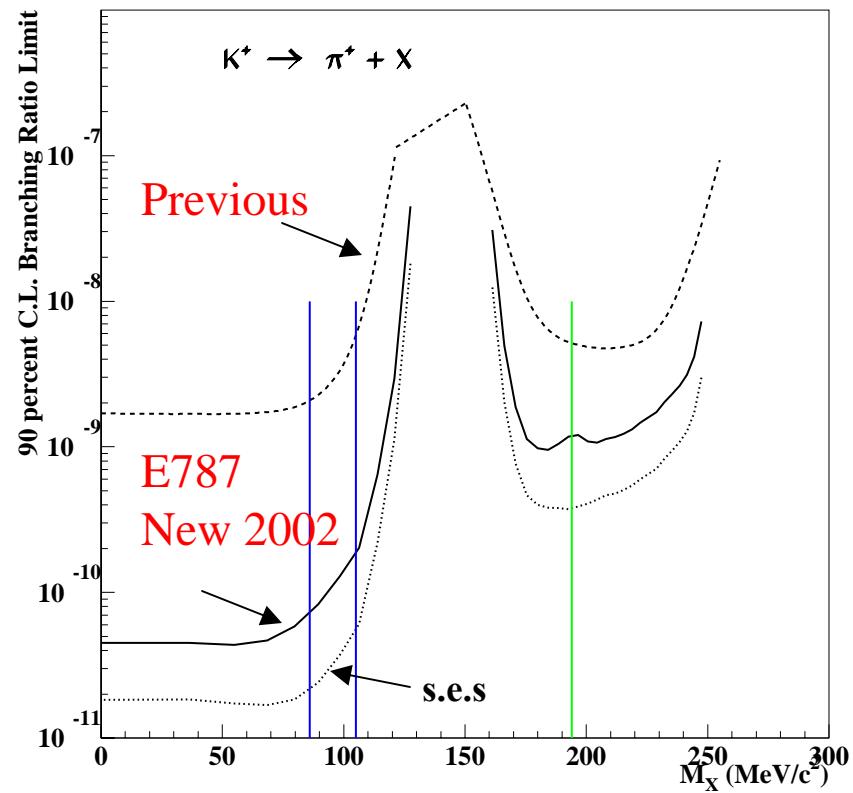
$$L_{eff} = \frac{1}{F} J_\mu \delta_\mu f : \mu \rightarrow e + f \text{ and } s \rightarrow d + f$$

	GFS	Experiment	F Limit (GeV)
$B(K^+ \rightarrow \pi^+ f)$	$\frac{1.3 \cdot 10^{14} GeV^2}{F^2}$	$< 5.9 \cdot 10^{-11}$ (E787) (2002)	$> 2 \cdot 10^{12}$
$B(\mu \rightarrow e f)$	$\frac{2.5 \cdot 10^{14} GeV^2}{F^2}$	$< 2.6 \cdot 10^{-6}$ (Jodidio)	$> 10^{10}$
$B(\tau \rightarrow e f)$	$\frac{2.5 \cdot 10^{14} GeV^2}{F^2}$	$< 2.6 \cdot 10^{-3}$ (ARGUS)	$> 3 \cdot 10^6$
COSMOLOGY			$10^9 < F < 10^{12}$

Limits on $K \rightarrow \pi X$



Branching Ratio vs. m_X



Probing CP Violation with Rare Kaon Decays

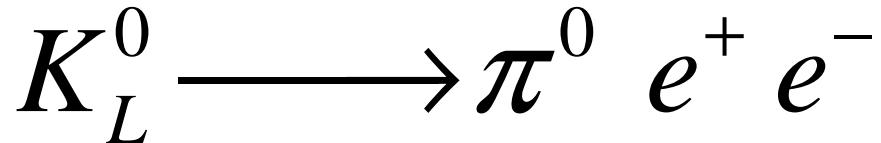
$$K_L^0 \longrightarrow \pi^0 e^+ e^-$$

Difficult to get at *short distance* physics due to long distance strong interaction effects and other complications. **Progress is being made.**

$$K_L^0 \rightarrow \pi^0 \bar{\nu} \nu$$

The Golden Mode! – but can it be measured?

SM Prediction: $R(K_L^0 \rightarrow \pi^0 \bar{\nu} \nu) \sim 4.1 \times 10^{-10} A^4 \eta^2 = 2.6 \pm 1.2 \times 10^{-11}$



$$B_{\text{exp}}(K_L^0 \rightarrow \pi^0 e^+ e^-) < 5.1 \times 10^{-10} \quad (\text{FNAL - E799 2001})$$

- CP conserving part - two photon intermediate state .

Can't be calculated reliably now. *Need $K_L^0 \rightarrow \pi^0 \gamma$*

- CP violating parts - single photon intermediate states

○ *Direct CP violation -- the goal !*

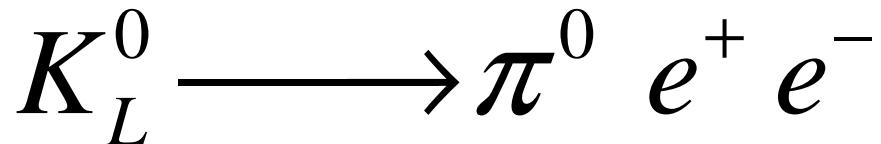
Same diagrams as $K \rightarrow \pi \bar{\nu} \bar{\nu}$:

$$R(K_L^0 \rightarrow \pi^0 e^+ e^-)_{CPV-dir} \sim 6.7 \times 10^{-11} A^4 \eta^2 = 4 \times 10^{-12}$$

○ Mixing - *Need $K_S^0 \rightarrow \pi^0 e^+ e^-$*

$$R(K_L^0 \rightarrow \pi^0 e^+ e^-)_{CPV-Mix} \sim |\epsilon|^2 \frac{\tau_L}{\tau_S} R(K_S^0 \rightarrow \pi^0 e^+ e^-)$$

- Background : $K_L^0 \rightarrow \gamma e^+ e^-$



- CP conserving part: two-photon intermediate state .

NA48 *Preliminary* results (2002):

$$B(K_L^0 \rightarrow \pi^0 \gamma\gamma) = (1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \times 10^{-6}$$

$$KTEV_{1999}: 1.68 \pm 0.10) \times 10^{-6}$$

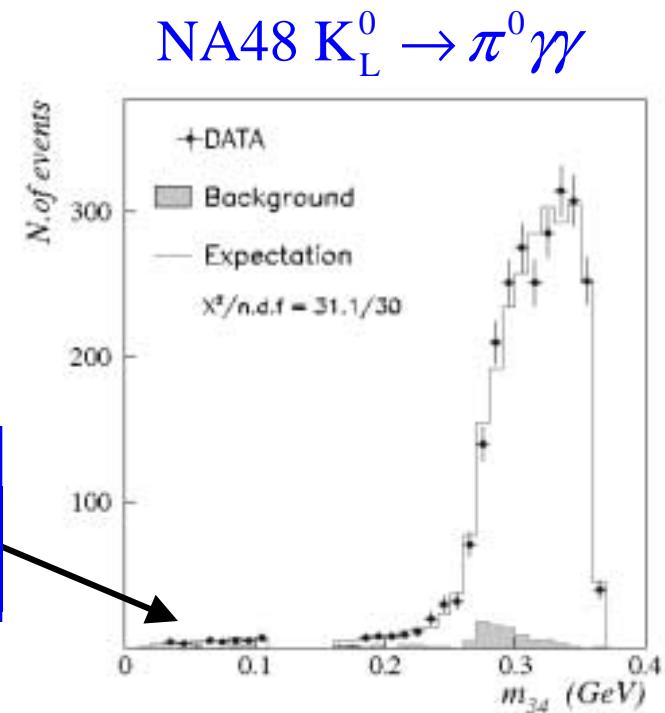
$$(a_v = -0.72 \pm 0.05 \pm 0.06_{KTEV})$$

$$CHPT: 1.5 \times 10^{-6}, \text{ shape par.: } a_v \sim 0.7$$

$$\left[B(K_L^0 \rightarrow \pi^0 \gamma\gamma)_{m_{\gamma\gamma} \in [30,110] \text{ GeV}, y \in [0,2]} < 0.6 \times 10^{-8} \right. \\ \left. a_v = -0.46 \pm 0.03 \pm 0.03 \pm 0.02_{NA48} \right]$$



$$B(K_L^0 \rightarrow \pi^0 e^+ e^-)_{CP} = (4.7 \pm 2.2) \times 10^{-13}$$



$$K_L^0 \longrightarrow \pi^0 e^+ e^-$$

- CP violating part due to mixing:

$$R(K_S^0 \rightarrow \pi^0 e^+ e^-)_{CPV-Mix}^{\text{CHPT}} \sim 5.2(a_s)^2 \times 10^{-9}, a_s \sim 1$$

$$\text{NA48 (2001): } B(K_S^0 \rightarrow \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$$

Use CHPT, $a_s < 5.2$: $B(K_L^0 \rightarrow \pi^0 e^+ e^-)_{CPV-Mix} < 4.4 \times 10^{-10}$

- Background : $K_L^0 \rightarrow \gamma \gamma e^+ e^-$

$$B(K_L^0 \rightarrow \pi^0 e^+ e^-)_{K_L^0 \rightarrow \gamma \gamma e^+ e^-} \sim 3 \times 10^{-10} \quad [\text{Greenlee}]$$

Experiments seeking $K_L^0 \rightarrow \pi^0 \bar{\nu}\bar{\nu}$

- Limit based on isospin and $K^+ \rightarrow \pi^+ \bar{\nu}\bar{\nu}$: $< 1.7 \times 10^{-9}$ • [Grossman, Nir]

- KTEV (FNAL) result:

$$R(K_L^0 \rightarrow \pi^0 \bar{\nu}\bar{\nu}) \equiv \frac{\Gamma(K_L^0 \rightarrow \pi^0 \bar{\nu}\bar{\nu})}{\Gamma(K_L^0 \rightarrow \text{all})} < 5.9 \times 10^{-7}$$

- KEK E391a *goal*: s.e.s. $10^{-10} - 10^{-9}$
- KOPIO (BNL) *goal*: s.e.s. $< 10^{-12}$, > 50 events



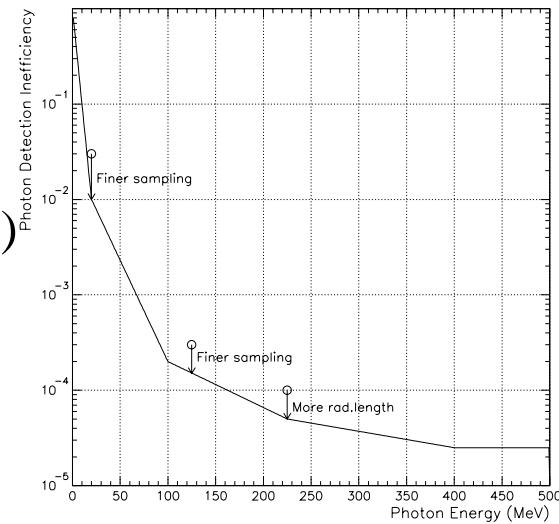
Primary Background: $K_L^0 \rightarrow \pi^0 \pi^0$ $R(K_L^0 \rightarrow \pi^0 \pi^0) \sim 10^{-3}$

Photon Vetoing

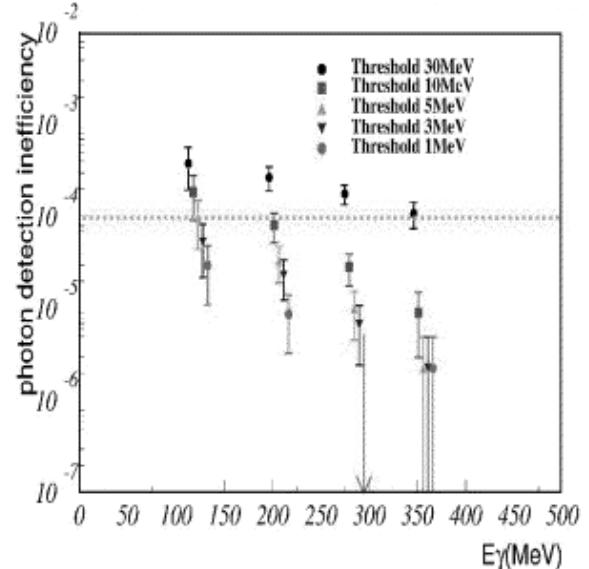
E787

$$\bar{\epsilon}_\gamma \sim 10^{-2} \text{ (20-100 MeV)} \\ \sim 10^{-4} \text{ (100-220 MeV)}$$

$$\bar{\epsilon}\pi^0 < 10^{-6}$$



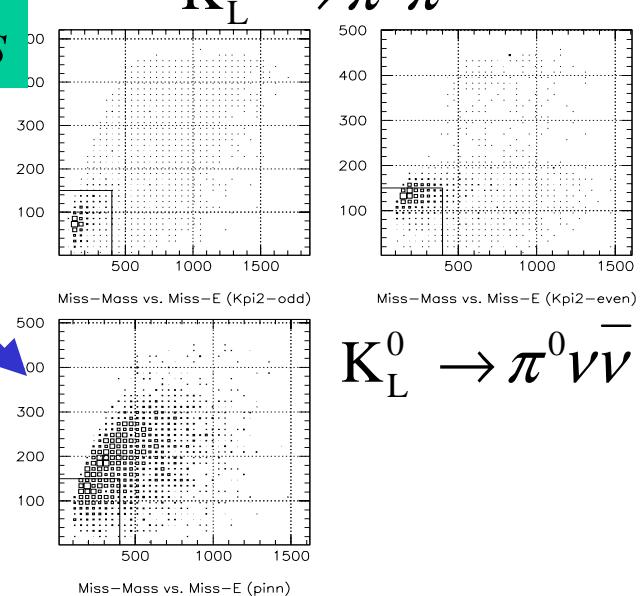
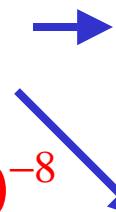
KEK *Photonuclear*
Inefficiency of γ detection



Photon vetoing & Kinematics:
Suppress events with low energy photons

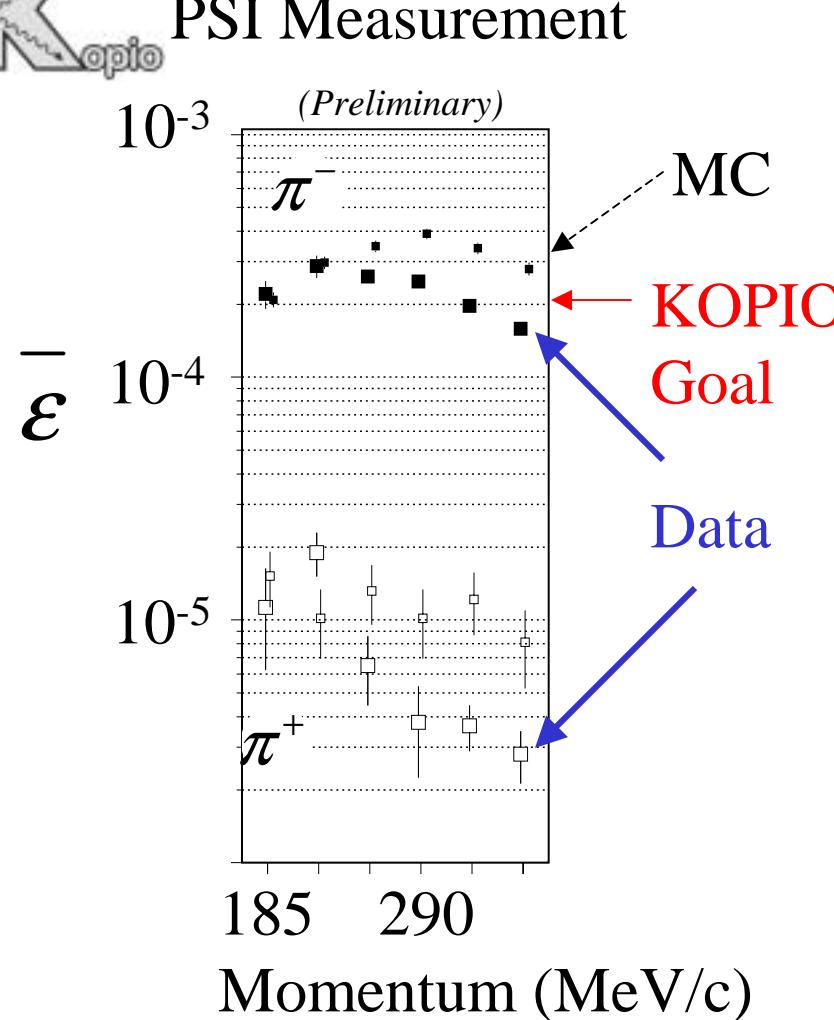
Missing mass ($2E_1^{miss}E_2^{miss}\cos\theta_{12}$) vs.
Missing energy ($E_1^{miss} + E_2^{miss}$)

$$\bar{\epsilon}\pi^0 < (10^{-4})(10^{-4}) = 10^{-8}$$



Charged Particle Vetoing

Example Background: $K_L^0 \rightarrow \pi^- e^+ \nu \gamma$

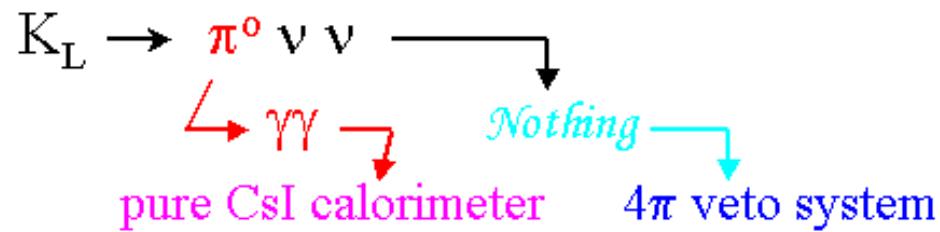
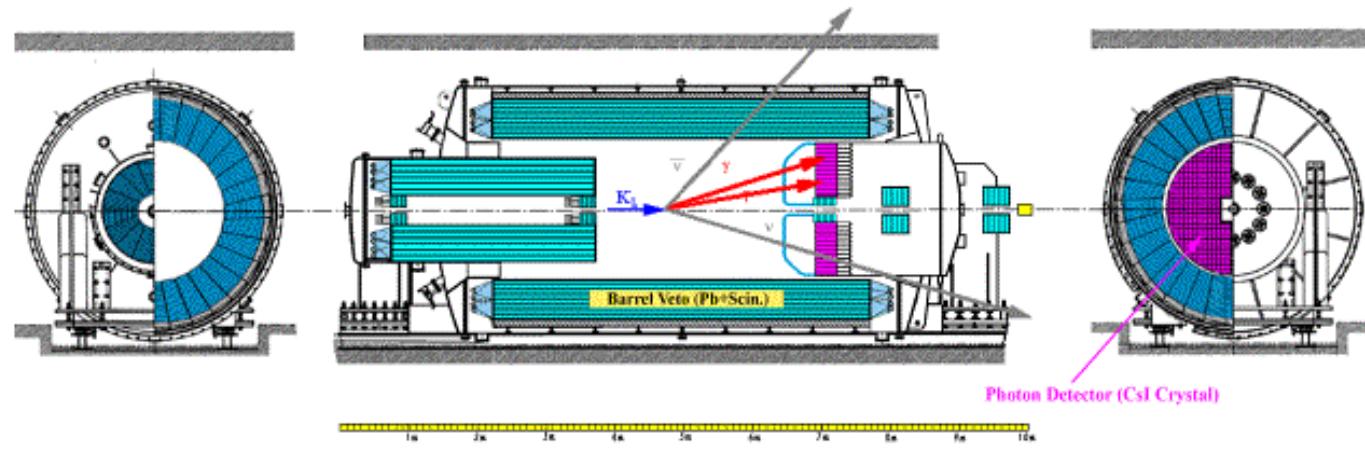


KEK: 1 GeV/c

Particle	$\bar{\epsilon}$
e^+	$(3.2 \pm 0.9) \times 10^{-4}$
π^+	$< 1.6 \times 10^{-5}$
e^-	$< 1.3 \times 10^{-4}$
π^-	$(6.0 \pm 0.6) \times 10^{-4}$

NIM A359, 478 (1995)

E391a Detector Setup



Features:

- * Pencil Beam
- * High acceptance
- * High P_T selection

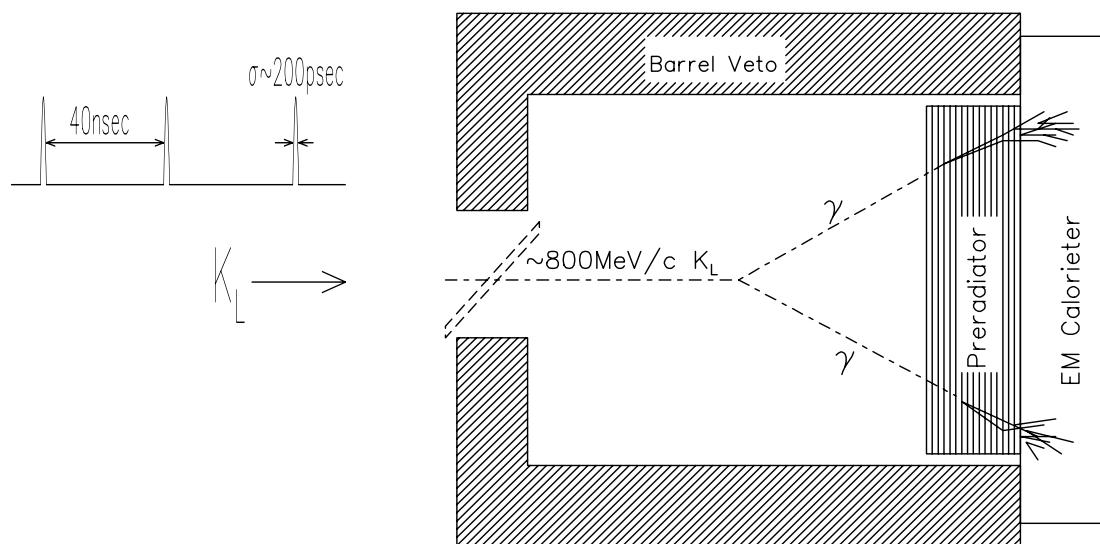
- * Pilot Project for JHF
- * Test reliance on extreme photon veto efficiency

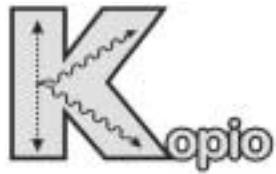


KOPIO: Measurement of $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

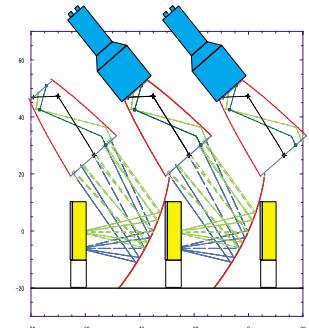
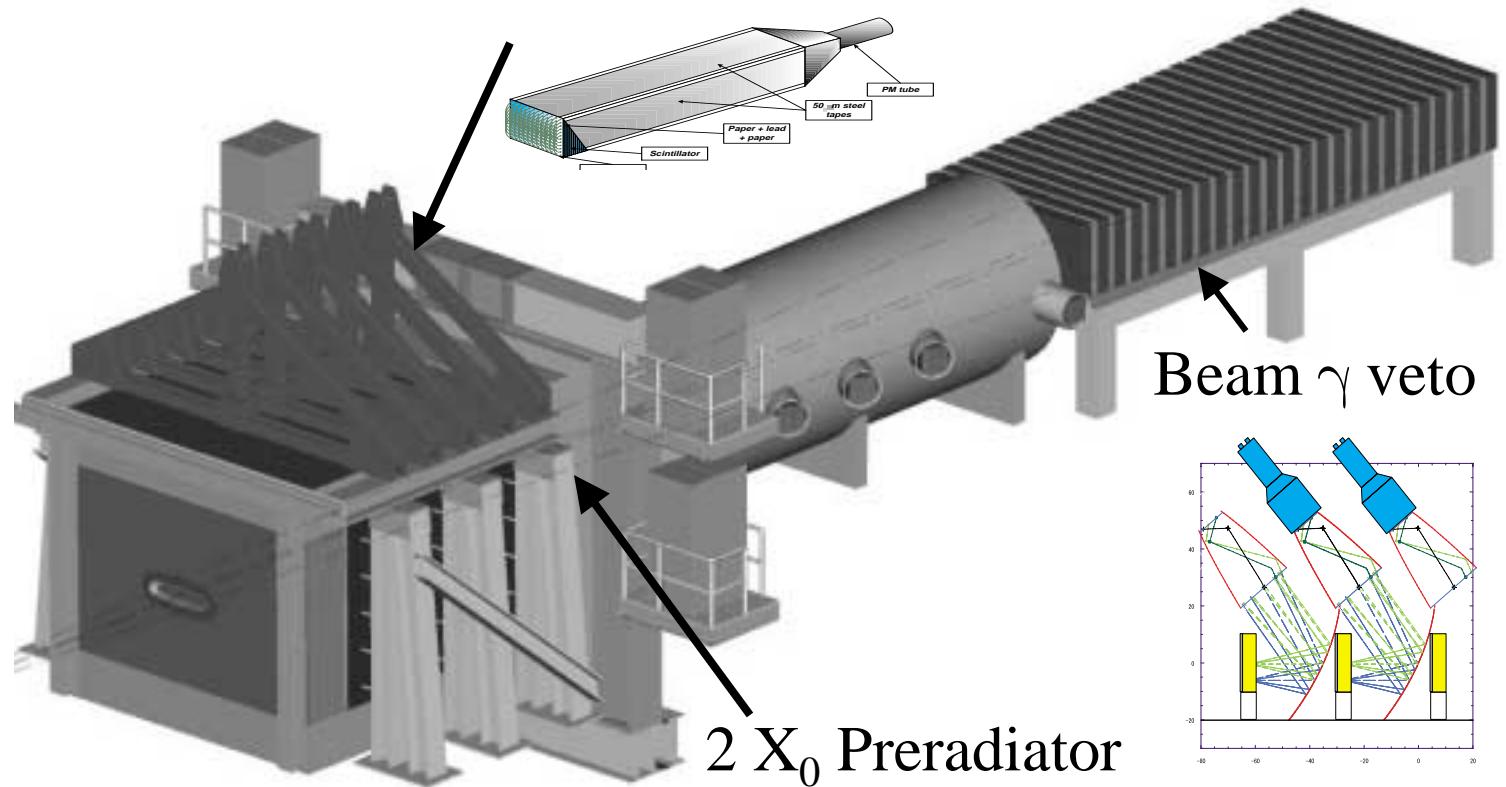
CONCEPTS

- Measure as much as possible:
Energy, position and *ANGLE* of each photon.
- Work in the C.M. system :
Use TOF to get the K_L^0 momentum.
- Maximize Photon Veto Efficiency
- Maximize Intensity of Microbunched Beam

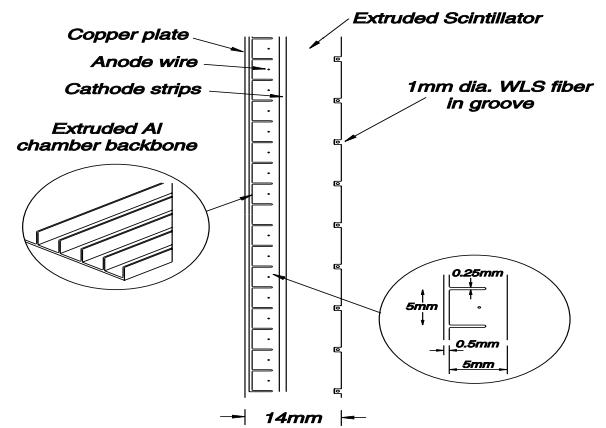




Shashlyk calorimeter



Parameter	Minimal Requirement	Expected Performance
E_γ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
θ_γ resolution (250MeV)	(25 – 30) mr	23 mr
t_γ resolution	$100ps/\sqrt{E}$	$50ps/\sqrt{E}$
x_γ, y_γ resolution(250MeV)	10mm	< 1mm
μ -bunch width	300ps	200ps
γ -veto inefficiency	$\bar{\epsilon}_{E787}$	$0.3\bar{\epsilon}_{E787}$

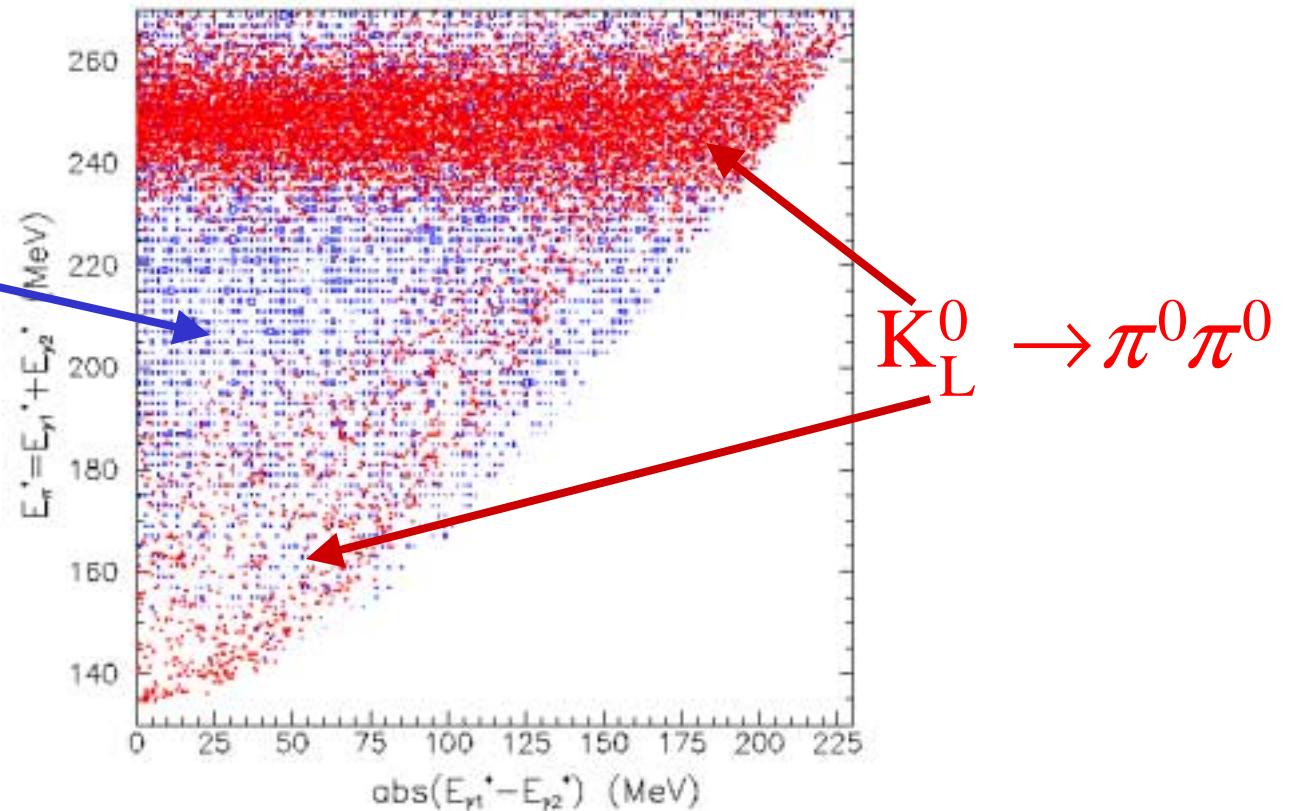
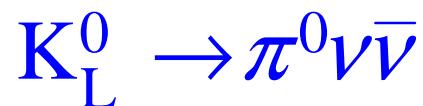




Kinematic suppression of backgrounds

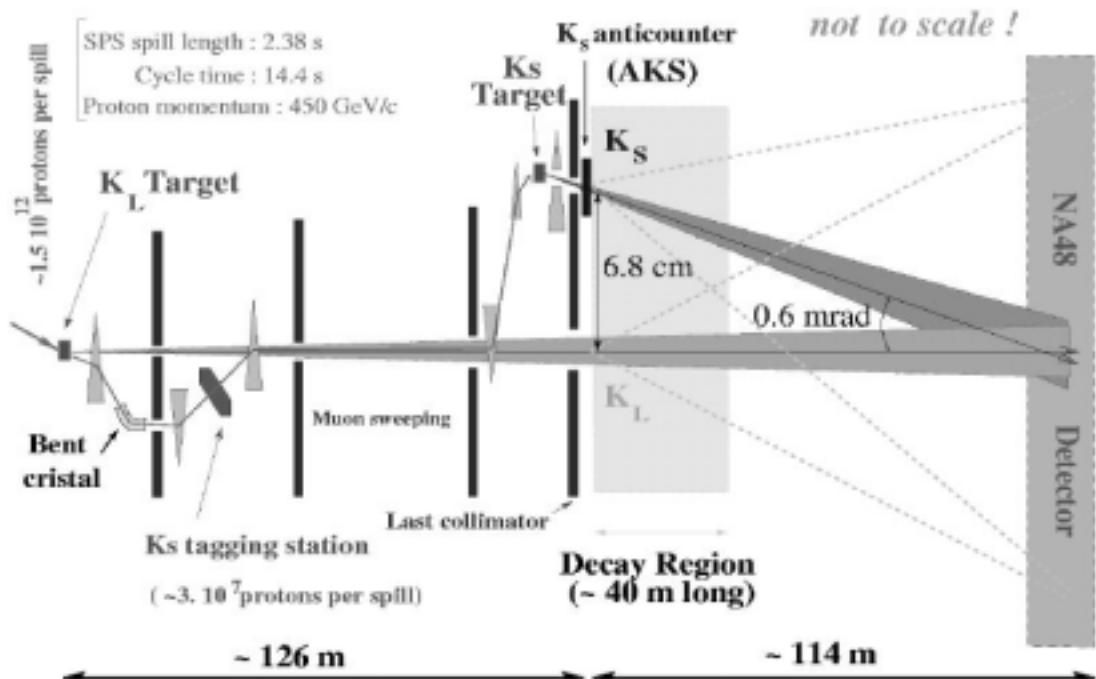
Goal: >50 Events with S/N>2

$E_{\pi^0}^* \text{ vs. } |E_{\gamma 1}^* - E_{\gamma 2}^*|$



NA48/1 Rare K Decay Studies (2002-)

The K_L and K_S beams



- Upgraded detectors and beamline.
- 100 x intensity
- Improved K_S target
- S.E.S~ 10^{-10}



NA48/1 - Motivation

- $K_S \rightarrow \pi^0 \ell^+ \ell^-$, $\ell = e, \mu$,
 - Bound Indirect CP Violation in $K_L \rightarrow \pi^0 \ell^+ \ell^-$ $< 10^{-10}$
- Search for CPV ~~inde~~ decays
 - $K_S \rightarrow 3\pi^0$, $K_S \rightarrow \pi^+ \pi^- \pi^0$
- Study of time dependent CPV asymmetry in $K_L \rightarrow \pi^+ \pi^- \gamma^*$
- Test of Chiral Perturbation Theory
 - $K_S \rightarrow \gamma\gamma$, $K_S \rightarrow \pi^0 \gamma\gamma$, $K_S \rightarrow \pi^0 \pi^0 \gamma\gamma$
- Study ~~K~~ Dalitz and semi-leptonic decays
- Semi-leptonic and radiative neutral hyperon
 - $\Xi^0 \rightarrow \Sigma^+ e^- \nu$, $\Xi^0 \rightarrow \Sigma^+ \mu^- \nu$, $\Xi^0 \rightarrow \Sigma^0 \gamma$, $\Xi^0 \rightarrow \Lambda \gamma$

R. Sacco (2002)

Summary and Outlook

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: 2 events seen
 $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.57 \pm^{1.75}_{0.82} \times 10^{-10}$ (E787)
Prospects: E949 (10 events) and CKM (100 events)
- $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ *Prospects :*
E391a (s.e.s. $< 10^{-9}$) and KOPIO (50 events).
JHF?
- Exotics: New results on $K_L^0 \rightarrow \pi^0 x, K_L^0 \rightarrow \pi^0 \gamma$ (E787)
Soon, $K \rightarrow \pi \mu e, others$ (KTEV/E799, BNL E865)

Summary and Outlook

- Radiative and semi-rare decays:

New results on $K_L^0 \rightarrow \pi^0 \gamma$, $K_S^0 \rightarrow \pi^0 e^+ e^-$,

$K_S^0 \rightarrow \pi^0 \gamma$ (NA48), $K_L^0 \rightarrow \pi^0 e^+ e^-$ (E799),

$K^+ \rightarrow \pi^+ \mu\mu$ (HYPER-CP), $K_S^0 \rightarrow \pi^\pm e^\mp \nu$ (KLOE)

Soon, others (KTEV/E799, BNL E865, NA48, KLOE)

New Experiments:

NA48/1: Rare decays of K's and hyperons,

CPV in K_S^0 decays

KLOE : ε'/ε , CPT, rare decays, test of CHPT